

LEVEL CONTROL SYSTEM FOR SHEET CASTING PROCESS

Cross-Reference to Related Application:

3 This application is being filed concurrently with related application Serial No.

4 _____, entitled "PROPORTIONAL FLOW CONTROL VALVE," assigned to the
5 assignee of the present invention, and naming James E. Ellis as the inventor.

7 | **Background of the Invention:**

8 || 1. Field of the Invention:

9 The present invention relates generally to sheet casting processes for producing
10 continuous tapes or sheets of material from a liquid slurry, and more particularly to an improved
11 level control system for maintaining the thickness of such tapes or sheets at a uniform, desired
12 thickness.

14 2. Description of the Related Art:

15 Continuous sheet casting processes are well known in the art for producing elongated
16 tapes or sheets of material of a desired thickness. For example, it is well known to cast ceramic
17 tape by depositing a liquid slurry, containing the ceramic material dissolved in a solvent, onto a
18 moving belt, passing the belt under a “doctor” blade to limit the thickness of the slurry, and
19 curing the tape by driving off the solvent in a heating step to leave an elongated tape of solid
20 ceramic material. Such a ceramic tape might be used, for example, in the manufacture of
21 interconnect substrates for micro-electronics.

22 In known sheet casting processes of this general type, the most common method of
23 controlling the thickness of the tape is to control the height of the aforementioned "doctor" blade.
24 A feedback control system has been used wherein the height of the tape is determined on the
25 downstream side of the "doctor blade," i.e., after the tape has passed beyond the "doctor" blade.
26 In some systems, the tape height is determined just beyond the "doctor" blade when the tape is
27 still "wet;" in other systems, the tape height is determined further downstream after the tape has
28 cured. In either case, information relating to the tape height is used to control the height of the

1 "doctor" blade above the moving belt in order to maintain the tape at a desired thickness.
2 However, raising and lowering the height of the "doctor" blade only goes so far in producing a
3 cast tape of uniform thickness.

4 Known casting systems often include valves for regulating the deposition of the slurry
5 onto the moving belt of the casting system. The slurry is supplied from a pressurized source, or
6 is pumped from an un-pressurized source, through a flexible tube. As the slurry can be abrasive
7 and damaging to common types of control valves, the flow of slurry is typically controlled by a
8 "pinch-off" control valve that extends about the flexible slurry supply tube. This pinch-off valve
9 is typically either open (i.e., out of contact with the supply tube) or closed (i.e., it pinches off the
10 supply tube). The slurry passing through the control valve is discharged into a reservoir located
11 above the moving belt. In turn, the reservoir releases slurry onto the moving belt upstream from
12 the "doctor" blade. It is known to include a sensor for sensing the slurry level in the reservoir to
13 open or close the control valve in order to selectively discharge additional slurry into the
14 reservoir. However, this process of regulating the level of slurry in the reservoir tends to be a
15 discontinuous, start-and-stop process, which does not contribute to the production of a tape with
16 uniform thickness. In addition, the application of excessive force to the supply tube during
17 pinch-off (excessive crushing force) can prevent the supply tube from fully-opening when full-
18 flow is later needed. Another problem that arises is that, depending on the type of tape being cast
19 and the nature of the slurry, the diameter of the slurry supply tube that fills the slurry reservoir
20 can vary, thereby changing the requirements of the pinch-off valve.

21 Moreover, solvent-based slurries pose a risk of explosion, as the solvent fumes are often
22 volatile. Known casting systems that sense the height of the tape downstream from the "doctor"
23 blade use electronic sensors that are positioned in close proximity to the tape. However, such
24 electronic sensors are subject to the creation of electrical sparks that, under some circumstances,
25 could cause a dangerous and damaging explosion.

26 Accordingly, it is an object of the present invention to provide a level control system for a
27 tape casting process capable of producing a casted tape with a thickness that is more uniform
28 than tapes that are currently produced.

1 It is another object of the present invention to provide such a level control system that is
2 relatively inexpensive and simple to construct.

3 Yet another object of the present invention is to provide such a level control system
4 which reduces the risk of explosion of volatile solvent fumes while sensing the height of the tape
5 being casted in real time.

6 A further object of the present invention is to provide such a level control system wherein
7 the supply of slurry to the moving belt can be better regulated in a continuous manner as opposed
8 to a start-and-stop manner.

9 These and other objects of the present invention will become more apparent to those
10 skilled in the art as the description of the present invention proceeds.

11

12 Summary of the Invention

13 Briefly described, and in accordance with one aspect thereof, the present invention relates
14 to a level control system that includes a moving belt, as well as a fluid reservoir for dispensing
15 slurry onto the moving belt. The reservoir is, in turn, supplied by additional slurry through a
16 control valve at a controlled rate. A blade, which may correspond with the front wall of the
17 reservoir, is positioned above the moving belt for regulating the thickness of the slurry that
18 passes beyond such blade. A lens is positioned generally proximate the moving belt for
19 receiving light reflected from the upper surface of the slurry; preferably, this lens is positioned
20 just above the slurry reservoir. A fiber optic cable extends between the lens and a remotely-
21 located light sensor for coupling light received by the lens to the light sensor. The light sensor
22 generates electrical signals in response to light received thereby, and a control circuit responsive
23 to the electrical signals created by the light sensor produces a control signal that drives a control
24 valve for regulating the flow of slurry therethrough. Preferably, the aforementioned control
25 valve is responsive to pneumatic pressure; in this case, the control circuit provides the control
26 signal to the control valve in the form of a regulated pneumatic pressure. In the preferred
27 embodiment of the present invention, the regulated pneumatic pressure is substantially inversely
28 proportional to the rate of flow of slurry through the control valve.

1 Brief Description of the Drawings

2 Fig. 1 is a cross-sectional drawing of a slurry casting system using a slurry reservoir
3 positioned over a moving belt, wherein the height of the slurry in the reservoir is controlled in
4 accordance with the present invention.

5 Fig. 2 is a perspective view of a slurry height sensor including a lens assembly, fiber
6 optic cable, and remotely located light sensor.

7 Fig. 3 is a close-up perspective view of the adjustable lens assembly shown in Fig. 2.

8 Fig. 4 is a perspective view of a control panel and control system housing for regulating
9 slurry thickness.

10 Fig. 5 is a perspective view of a preferred proportional control valve for use in practicing
11 the present invention.

12 Fig. 6 is a circuit schematic drawing showing the control circuitry used to regulate the
13 flow of slurry through the proportional control valve.

14 Fig. 7 is a circuit schematic drawing showing the circuitry used to process the light sensor
15 signals generated by the light sensors.

16 Fig. 8 is a pneumatic schematic showing plumbing connections between the air pressure
17 source, a main air valve, a proportional air valve, related check valve, and regulated air pressure
18 output port.

19

20 Detailed Description of the Preferred Embodiments

21 Referring to Fig. 1, a portion of a slurry casting system is shown in cross-section,
22 including a level control system, designated generally by reference numeral 10, for controlling
23 the thickness of slurry 12. The slurry casting system includes a moving belt 14 on which slurry
24 12 is carried in the direction indicated by arrow 20. Slurry 12 is sourced by a slurry reservoir 15
25 which includes a front wall 16 (also known as a "blade"), a rear wall 18, and two connecting side
26 walls (not shown) extending therebetween to form a box-like container positioned over moving
27 belt 14. Slurry reservoir 15 is filled with a supply of slurry 20 that is dispensed onto moving belt
28 14. Note that front wall 16 does not extend all the way down to moving belt 14; accordingly, a

1 quantity of slurry 12 passes under the lower edge of front wall 16 and moves away from reservoir
2 15 along with moving belt 14. The height, or thickness, of slurry 12 is a function of 1) the slurry
3 consistency; 2) the height of the lower edge of front wall 16 above moving belt 14; 3) the speed
4 of moving belt 14; and 4) the height of slurry 20 within reservoir 15. It is common to position a
5 second, separate blade (not shown) above moving belt 14 downstream from front wall 16 to
6 further regulate the thickness of the cast slurry that passes beyond reservoir 15. The level control
7 system described herein greatly improves upon the accuracy of such dual-blade systems.

8 As mentioned above, one of the factors which can influence the thickness of the cast
9 slurry 12 is the height of slurry 20 in reservoir 15. Accordingly, it is important to control the
10 height of slurry 20. In order to maintain such height relatively constant, new slurry must be
11 added to reservoir 15 at the same rate that slurry leaves reservoir 15 under front wall 16. In Fig.
12 1, slurry 20 is replenished by a slurry supply tube 22 that is coupled to a pressurized source of
13 slurry 26 by flow control valve 24. Flow control valve 24 must be operated to fill slurry
14 reservoir 15 with slurry 20 at a controlled rate in order to maintain the height of slurry 20
15 relatively constant. Flow control valve 24 is located as close to the reservoir as practical; it
16 provides real-time flow control of the slurry to reservoir 15.

17 Also shown in Fig. 1 is a sensor lens assembly 28 disposed relatively near moving belt
18 14, and more particularly in the preferred embodiment, just above slurry reservoir 15 for
19 receiving light reflected from the upper surface of slurry 20. Sensor lens assembly 28 includes a
20 lens 30 which shines a beam of light 32 downward toward slurry 20; this beam of light is
21 supplied remotely from a light source. Light beam 32 is partially reflected off of the surface of
22 slurry 20 and is received by lens 32. As shown in Fig. 1, a pair of optical fibers 34 extend within
23 sensor lens assembly 28, one to bring the source of the light to lens 30 from the remote source,
24 and a second to carry reflected light received by lens 32 to a remotely-located sensor assembly.
25 As will be explained in greater detail below, this reflected light can be used to determine the
26 relative height of slurry 20 within reservoir 15, and this height information can be used to
27 regulate control valve 24 in order to maintain such height relatively constant.

28 In the preferred embodiment of the present invention, sensor lens assembly 28 also

1 includes a second lens 36 and second pair of optical fibers 40 for transmitting and receiving a
2 second light beam 38. Lens 36 and optical fibers 40 are used to sense an "overfill" condition
3 wherein the height of slurry 20 has risen above some maximum safe threshold. Those skilled in
4 the art will appreciate that lens elements 30 and 36, and optical fiber pairs 34 and 40, do not
5 conduct any electrical current. Accordingly, they present no risk of creating sparks that could
6 ignite volatile fumes emitted by slurry 20.

7 Turning to Figs. 2 and 3, sensor lens assembly 28 is shown in greater detail, along with a
8 related light sensor assembly and interconnecting flexible cable. Sensor lens assembly 28,
9 containing lens 30 and lens 36, is movably mounted in height adjustment mechanism 42 that
10 provides vertical adjustment of sensor lens assembly 28 relative to the upper surface of slurry 20.
11 Height adjustment mechanism 42 is mounted on or above slurry reservoir 15 so that sensor lens
12 assembly 28 can continuously monitor the level of slurry 20 within reservoir 15. The focal point
13 of lens 30 is approximately .900 inches on a white body material; the closer the lens is to the
14 slurry, the higher the resolution that is obtained. When operating normally, slurry 20 is
15 maintained within a range of 0 to .5 inches below the focal point of lens 30. Height adjustment
16 mechanism 42 can raise the height of sensor lens assembly 28 up and down within approximately
17 a 2.5" rough adjustment, and a one-half inch accurate adjustment. The adjustment micrometer
18 can adjust the sense point within one thousandth of an inch. The rough adjustments are made first
19 via adjustment knob 50, followed by fine adjustment using micrometer 52, in order to control the
20 height of slurry 20 in reservoir 15.

21 As shown in Fig. 2, sensor lens assembly 28 is coupled by an interconnecting flexible
22 cable 44 to a light sensor assembly 46. Flexible cable 44 houses optical fiber pairs 34 and 40
23 (see Fig. 1) which extend between sensor lens assembly 28 and light sensor assembly 46. Light
24 sensor assembly 46 includes built in light sources that provide light which is conveyed by optical
25 fiber pairs 34 and 40 down to lenses 30 and 32, respectively. Light sensor assembly 46 also
26 includes light sensors and related receiving amplifiers. The light sensors are responsive to light
27 received by lenses 30 and 32; these light sensors are coupled to the receiving amplifiers. The
28 receiving amplifier that processes the light signal sensed by lens 30 (slurry level) is analog in

1 nature, and generates an output signal that is proportional to the sensed height of the slurry level;
2 that receiving amplifier is compensated to linearize the received input light signal, and generates
3 an output signal indicative of the number of inches between lens 30 and the upper surface of the
4 slurry 20 in slurry reservoir 15. In contrast, the receiving amplifier which is responsive to light
5 received by lens 32 is binary in nature, and provides a binary output signal indicating either a
6 normal condition or an overfill condition. Again, light sensor assembly 46, which uses electrical
7 circuitry, is a potential spark generator, and is therefore preferably located remote from the
8 volatile environment of the slurry. No electrical current need pass within flexible cable 44. As
9 will be explained in greater detail below, the housing for light sensor assembly 46 also houses a
10 micro-controller circuit board, which includes a non-volatile memory module for storing
11 calibration information.

12 Fig. 4 illustrates a controller cabinet 54 for controlling the rate at which slurry is added to
13 slurry reservoir 15. Controller cabinet 54 is likewise a potential spark generator, and is mounted
14 as far as practical from the volatile vapors given off by the slurry. Controller cabinet 54 houses a
15 programmable logic controller (PLC), a proportional air regulator, a main air cutoff valve,
16 keypad, display, start switch, analog power supply, digital power supply, alarm and E-stop
17 (emergency stop). Controller cabinet 54 has an AC inlet using a standard plug 76 for receiving
18 110 volt alternating current, and a main air inlet 78 for receiving pressurized air from a source
19 that provides 80 PSI air at the rate of .1 CFM. Fuses 70, located on front panel 56 of controller
20 cabinet 54, protect electrical components from electrical shorts and/or excessive current
21 conditions.

22 Keypad 58 is mounted upon front panel 56 of controller cabinet 54, and is preferably a
23 twelve key unit that is configured similar to a touch-tone telephone keypad and/or simple
24 calculator keypad. Ten keys correspond to the numbers 0-9, and two further keys serve as
25 "Enter" and "Clear" keys. Keypad 58 is used for data entry and for controlling specific functions
26 within the controller. Many of the keys are multifunctional, depending on the operation in
27 progress.

28 Front panel 56 of controller cabinet 54 also includes a liquid crystal display unit 60,

1 preferably one which is capable of displaying four lines of output. LCD display unit 60 is used
2 to provide operator feedback; for example, it may be used to display height, set point, output
3 level, alarm status, and also to display data being entered by a user on keypad 58. The height and
4 set point are preferably programmed to be displayed by LCD display unit 60 at all times so that
5 important system parameters can be monitored without interruption. Other functions such as
6 "valve off," and "manual" versus "auto" mode, can also be displayed. In "auto" mode, LCD
7 display unit 60 displays real-time level, set point, and output level, in .0002" increments.

8 Housing 46 (see Fig. 2), which contains the light sensor assembly and micro-controller
9 circuit board, preferably mounts to region 64 of front panel 56 of controller cabinet 54 with four
10 shoulder screws 66 (see Fig. 4). A short connector cable (not shown) electrically couples micro-
11 controller circuit board output connector 47 (see Fig. 2) to input connector 62 (see Fig. 4) on
12 front panel 56 of controller cabinet 54. The sensor amplifiers, optical fibers, and lenses that are
13 included in sensor lens assembly 28, flexible cable 44, and light sensor assembly 46, create a
14 unique system that must be factory calibrated to work correctly with the main controller circuitry
15 housed in controller cabinet 54; internal adjustments cannot be made in the field. Each time the
16 system is started, the sensor assembly micro-controller circuit board of sensor assembly 46
17 uploads calibration information to the main controller board within controller cabinet 54.

18 Connector 68, located on front panel 56 of controller cabinet 54, is a regulated air
19 pressure outlet port for use in driving the proportional flow cut-off valve 24 shown schematically
20 in Fig. 1. Controller cabinet 54 includes therein a proportional air-regulating valve. In
21 accordance with the electrical signals received from light sensor assembly 46 at connector 62 of
22 controller cabinet 54, the proportional air-regulating valve receives a 0-10 volt DC signal from a
23 digital-to-analog converter on the controller circuit board to proportionally vary the air pressure
24 output to connector 68. The regulated air pressure delivered to connector 68 is used to drive
25 control valve 24, which in turn regulates the flow of slurry therethrough. If the height of slurry
26 20 within slurry reservoir 20 is significantly below the set height, then the air pressure output by
27 connector 68 is relatively low, or zero, for allowing control valve 24 to fully open. On the other
28 hand, if the height of slurry 20 within slurry reservoir 15 is approximately at the set height, then

1 the air pressure output by connector 68 is relatively high for constricting, or even closing off,
2 control valve 24.

3 Turning briefly to Fig. 8, main air pressure inlet connector 78 of controller cabinet 54 is
4 coupled by pipe 79 to the inlet 81 of main air valve 130 and also to the inlet 83 of proportional
5 flow air valve 136 for supplying a source of 80 PSI air pressure. Main air valve 130 is normally
6 open during power-off conditions. Accordingly, when electrical power is off, main air valve 130
7 is open and supplies 80 PSI air pressure, via output port 85 to the inlet 87 of unidirectional check
8 valve 89. Outlet 91 of check valve 89 is coupled to regulated pressure port connector 68, and
9 thereby supplies 80 PSI air pressure to connector 68 whenever electrical power is off. As will be
10 explained below, in this instance, the control valve that supplies slurry to the casting system is
11 held closed. Note that, during power outage, proportional air valve 136 is off, and air pressure
12 supplied to inlet 83 of valve 136 is vented to exhaust port 93. In other applications of valve 136
13 apart from the present level control system, exhaust port 93 might be vented to atmosphere.
14 However, in the present case, exhaust port 93 is coupled to the inlet 87 of check valve 89, so any
15 air pressure vented by exhaust port 93 of valve 136 simply merges with the air pressure supplied
16 by outlet 85 of main air valve 130.

17 Still referring to Fig. 8, when electrical power is on, main air valve 130 is turned off, and
18 proportional air valve 136 is enabled. In a manner to be described below, valve 136 provides a
19 regulated air pressure, between zero and 70 PSI, at its outlet 95 for coupling to connector 68. As
20 the pressure supplied by valve 136 increases, the flow of slurry through flow control valve 24
21 (see Fig. 1) decreases in an inversely proportional manner.

22 Fig. 5 illustrates a proportional flow control valve, designated generally by reference
23 numeral 82, for controlling the flow of a fluid through a flexible tube. The function of flow
24 control valve 82 is to proportionally control the amount of flow of slurry, or other process fluid,
25 as determined by a controlled amount of air pressure received from controller cabinet 54.
26 Increased air pressure causes increased pinch-off of slurry supply tube 22 (see Fig. 1), which
27 reduces output flow of slurry from the valve; in contrast, decreasing air pressure increases flow
28 from flow control valve 82.

1 The linear relationship between the pressure applied to actuator 84 of control valve 82
2 and the flow of fluid therethrough can be enhanced by partially deforming, or "pre-crushing," the
3 flexible tube through which the fluid passes, even when control valve 82 is "open". In other
4 words, when one initially begins to deform, or pinch, a flexible tube, fluid flow therethrough is
5 not significantly impacted. It is only after the tube has been significantly deformed from its
6 original circular cross-section to a certain pre-crushed condition that fluid flow begins to become
7 restricted. The precise amount of pre-crush required depends in part upon the nature of the fluid
8 and the pressure applied to the fluid by its source. Once such pre-crush point is reached, further
9 deformation of the tube results in substantially proportional decreases in the flow rate through the
10 tube. It is therefore advantageous to "pre-crush" the tube when the valve is "open" to improve
11 the overall proportionality of control valve 82 as the tube is further compressed. In this manner,
12 the entire travel of actuator 84 and pushrod 90 can be used to vary the degree of flow through the
13 flexible tube.

14 The flexible tube through which the fluid flows (e.g., flexible tube 22 of Fig. 1) is placed
15 upon a tube passageway 104, surrounded by a first jaw 102 and a second jaw 106. Jaws 102 and
16 106 selectively engage opposing sides of the flexible tube that is guided over passageway 104.
17 Jaw 106 is relatively fixed during operation, although the initial position of jaw 106 can be
18 varied by rotating adjustment knob 110 for reasons that will be explained below. On the other
19 hand, jaw 102 is movable and is secured to the end of an axially-slidable pushrod 90. As
20 pushrod 90 slides back and forth along its axis, jaw 102 moves back and forth therewith, thereby
21 varying the separation distance between jaws 102 and 106. The starting point of jaw 102,
22 relative to the end of pushrod 90, can be varied by use of tee-selector pin 109 in cooperation with
23 adjustment holes 108. The lower end of tee-selector pin 109 is received within a corresponding
24 hole formed in the end of pushrod 90. Tee-selector pin 109 and adjustment holes 108 provide for
25 a gross adjustment of the separation distance between jaws 102 and 106 to facilitate the use of
26 flow control valve 82 with flexible tubes of widely-different diameters.

27 The end of pushrod 90 opposite jaw 102 is coupled to an actuating cylinder housed within
28 actuator 84. Actuator 84 is preferably of the type commercially available from SMC Corporation

1 of America, formerly known as SMC Pneumatic, Inc., of Indianapolis, Indiana under Part No.
2 NCQ2B63-30D, and has a cylinder head/disk that is 63 mm. in diameter. Such disk normally
3 comes with a peripheral rubber seal ring around its periphery to form a sliding seal with the
4 surrounding cylinder; applicant has found it to be advantageous to grind away a portion of such
5 peripheral rubber ring to minimize friction between the disk and its surrounding cylinder.
6 Actuator 84 includes an input pressure port 86 that is coupled to output pressure connector 68
7 (see Fig. 4) of controller cabinet 54 for receiving the regulated air pressure supplied thereby.
8 Pushrod 90 can be advanced to the right (relative to Fig. 5) to decrease the separation distance
9 between jaws 102 and 106 as the regulated air pressure applied to port 86 is increased. Flow
10 control valve 82 also includes two series of disc springs (so-called "Belleville washers") 114 and
11 116, each of which includes a central aperture for allowing pushrod 90 to slide therethrough.
12 There are preferably approximately 70 of such disc springs in all. In addition, pushrod 90 has a
13 series of successive holes formed therein into which the lower end of Tee pin 112 may be
14 inserted.

15 Preferably, each disc spring is capable of allowing .013" of displacement when full 70
16 PSI air pressure is applied to input pressure port 86. If, for example, the separation distance
17 between jaws 102 and 106 is to be varied by .25" when moving between full, unrestricted flow
18 and zero, pinched-off flow, then the travel requirement of .25" is divided by the displacement per
19 spring, or .25"/.013," which equals 19 springs. Accordingly, Tee pin 112 is moved to a location
20 separating 19 springs 114 between Tee pin 112 and stationary wall 100. In this manner, Tee pin
21 112 and disc springs 114 control the amount of travel of pushrod 90 between zero and full
22 pressure. When full pressure is released, disc springs 114 serve as a return spring mechanism for
23 moving pushrod 90 back toward the left (relative to Fig. 5), increasing the separation distance
24 between jaws 102 and 106, and increasing the flow rate through the flexible tube passing
25 between such jaws.

26 When configuring flow control valve 82 for use, the user must first determine the travel
27 requirements of pushrod 90 for a given casting process. A given casting process will establish
28 the maximum flow rate, and supply tube diameter required. There are three general steps which

1 need to be applied to determine such travel requirements. First, one must determine the tube size
2 required for the process cast. If the tube size is too large, the amount of jaw travel to move
3 between unrestricted flow and the fully-closed position will be only a small fraction of the
4 diameter of the tube, thereby reducing the resolution of control valve 82. If, on the other hand,
5 the diameter of the tube is too small, then the maximal flow rate through the tube will not be
6 sufficient to keep up with the demand of the system. Secondly, the user must determine the
7 actual stroke requirement of control valve 82. For example, it might be determined that the
8 separation distance between jaws 102 and 106 is to be varied by .25" when moving between full,
9 unrestricted, pre-crushed flow and zero, pinched-off flow. Lastly, control valve 82 must be
10 configured to put out the required stroke.

11 For example, assume that a particular casting process requires a tube OD (outer diameter)
12 of .75 inch and a tube ID (inner diameter) of .50 inch (i.e., a tube wall thickness of .125 inch);
13 further assume that the supply tube will supply enough slurry to outrun the cast, i.e., to add slurry
14 to the reservoir at a faster rate than slurry leaves the reservoir, even when the supply tube inner
15 diameter is "pre-crushed," or pinched off, by one-half (i.e., the distance between opposing inner
16 walls is one-half that of the original un-pinched inner diameter). In this case, the travel
17 requirement for pushrod 90 of valve 82 is the supply tube inner diameter divided by two.
18 Accordingly, since the original inner diameter was assumed to be .5 inch, pushrod 90 of control
19 valve 82 needs to have a travel distance of .25 inch.

20 Flexible slurry supply tube 22 (see Fig. 1) is placed in the valve tube passageway 104.
21 Continuing with the example described above wherein .25 inch of travel is desired, Tee selector
22 pin 112 is positioned to select 19 disc springs within group 114 A relatively small amount of air
23 pressure is then applied to input pressure port 86 of actuator 84 to get Tee pin 112 to snug-up the
24 19 selected disc springs within group 114 against valve dividing wall 100; this corresponds to the
25 fully-open position of control valve 82. The user then loosens Allen-head adjustment screw 94
26 of full-open clamp collar 92 until clamp collar 92 lies adjacent the opposite side of valve
27 dividing wall 100, and re-tightens Allen-head adjustment screw 94.

28 Now, input pressure port 86 of actuator 84 is pressurized to full pressure (70 psi),

1 corresponding to the fully-closed position; the user then loosens Allen-head adjustment screw 98
2 of full-closed clamp collar 96 until clamp collar 96 lies adjacent dividing wall 97 of control valve
3 82, and re-tightens Allen-head adjustment screw 98. Next, adjustment knob 110 is rotated to
4 move jaw 106 to just pinch off slurry supply tube 22 completely. It will be noted that it may be
5 necessary to move Tee pin 109 into a different adjustment hole 108 within jaw 102 in order to
6 get the face of jaw 102 at an adequate start position so that tube 22 can be just barely pinched off
7 when actuator 84 is fully pressurized. This procedure limits travel of pushrod 90, and jaw 102,
8 between the pre-crushed (minimal pressure) condition and the fully-off (full 70 PSI pressure). If
9 greater or lesser amounts of travel are needed, the procedures already described above are
10 repeated to calculate the number of disc springs 114 to be engaged by Tee pin 112, and to reset
11 the positions of Tee pin 109, adjustment knob 110, and clamp collars 92 and 96. Proportional
12 cut-off control valve 82 is now ready for use.

13 Those skilled in the art will appreciate that, upon being configured in the manner
14 described above, actuator 84 is adapted to vary the separation distance between jaws 102 and 104
15 between an initial separation distance (the pre-crushed condition) that permits full slurry flow,
16 and a shut-off separation distance just sufficient to fully pinch-off the flow of any slurry through
17 flexible slurry supply tube 22. The initial separation distance is small enough to at least partially
18 deform, or pre-crush, flexible supply tube 22, while being large enough to avoid any significant
19 restriction of the flow of fluid therethrough. In contrast, the shut-off separation distance is just
20 small enough to essentially block the flow of fluid through supply tube 22.

21 Turning to the schematic of Fig. 6, the main system controller housed within control
22 panel 54 (see Fig. 4) includes a programmable logic controller (PLC) 120 of the type
23 commercially available from Triangle Research International, Inc. of San Jose, California under
24 Model No. T100MD-16-16. PLC 120 includes 16 digital input terminals, 16 digital output
25 terminals, and 5 analog input/output terminals. PLC 120 includes a built-in liquid crystal display
26 (LCD) interface for coupling to LCD display module 60. LCD display module 60 is also
27 commercially available from Triangle Research International, Inc. under Part No. LCD 420;
28 display module 60 is a 4-line by 20 character-per-line backlit LCD display often used in

1 conjunction with T100MD programmable logic controllers.

2 PLC 120 uses 7 of its digital input terminals to receive input signals from keypad 58.

3 Keypad 58 is a Grayhill Series 88 sealed keypad commercially available under Part No.

4 GH5018-ND from Digi-Key Corporation of Thief River Falls, Minnesota. PLC 120 of Fig. 6

5 also includes an RS232 communication port coupled to conductors 121, 123, and 125 which can

6 be used to conduct serial communications with PLC 120. Before PLC 120 is actually used to

7 control a slurry casting operation, it must first be programmed. In this initial programming

8 phase, the RS232 communication port of PLC 120 is coupled to the serial port of a host

9 computer for receiving operating instructions (software code) used to program the steps

10 performed by PLC 120. PLC 120 includes an internal EEPROM program memory for storing up

11 to 6016 words of software instructions. Once programmed, the RS232 port is used to couple

12 PLC 120 to the sensor interface board 124 housed within light sensor assembly 46, via output

13 connector 47 (see Fig. 2) and input connector 62 (see Fig. 4).

14 PLC 120 also includes an internal digital-to-analog controller for generating an analog

15 output signal ranging between zero and 10 volts D.C. As shown in Fig. 6, one such analog

16 output terminal is coupled by conductor 135 to a control terminal of proportional air valve

17 controller 136. Proportional air valve 136 is of the type commercially available from SMC

18 Corporation of America, formerly known as SMC Pneumatic, Inc., of Indianapolis, Indiana

19 under Part No. ITV 2030-31N2L4. This valve serves to regulate output air pressure in

20 accordance with an analog voltage applied thereto. Moreover, the output air pressure is regulated

21 to vary proportionally with the magnitude of the analog voltage applied thereto. PLC 120

22 computes an eight-bit digital value indicative of the degree to which proportional air valve 136

23 should be opened in order to supply the desired amount of air pressure to actuator 84 of control

24 valve 82; that eight-bit digital value is then transformed by PLC 120 into a corresponding analog

25 voltage supplied on conductor 135 for driving proportional air valve 136. In turn, proportional

26 air valve 136 supplies a regulated air pressure (via port 68 on front panel 56 of control panel 54)

27 to air pressure input port 86 of actuator 84.

28 PLC 120 uses one of its digital output terminals to control main air solenoid 130

1 associated with a main air valve (not shown); this main air valve is preferably of the type
2 commercially available from above-mentioned SMC Corporation of America under Part No.
3 VQZ242-5L-N7T. This main air valve is interposed between the main air inlet port 78 of control
4 panel 54 and proportional air valve 136. Conductor 129 is coupled between such output terminal
5 and main air solenoid 130. If PLC is not powered-up, this output terminal is a high impedance;
6 when PLC 120 is powered-up, and operating normally, conductor 129 is grounded by PLC 120,
7 allowing current to flow through main air solenoid 130, thereby supplying the main air pressure
8 (e.g., 80 PSI) to the air input side of proportional air valve 136.

9 As shown in Fig. 6, another digital output terminal of PLC 120 is used to activate a
10 buzzer 132 via conductor 133, which serves an internal audible alarm for signaling an alarm
11 condition. If desired, an alarm can also be created remotely using power relay 134. Power relay
12 134 is coupled to another digital output terminal of PLC 120 via conductor 135; when such
13 output terminal moves low (to ground voltage), the primary coil of power relay 134 is activated,
14 and power relay closes a secondary switching contact that can handle greater amperage. The
15 secondary contacts of power relay 134 are accessible via port 80 on control panel 54 (see Fig. 4).

16 Before leaving Fig. 6, it will be noted that block 122 of Fig. 6 represents components that
17 are located outside control panel 54, more particularly, components housed within light sensor
18 assembly housing 46. Analog sensor amplifier 128 is coupled by fiber optics within flexible tube
19 44 to level sensor lens 30, while overfill sensor amplifier 126 is coupled by fiber optics within
20 flexible tube 44 to overfill sensor lens 36. Amplifier 128 is preferably of the type commercially
21 available from SUNX Sensors USA, a division of Ramco Inc. of West Des Moines, Iowa under
22 the Model Name FX-11A Analog Output Fiber-Optic Amplifier. Such sensor amplifier provides
23 an analog output signal in the range of 1-5 volts D.C., depending upon the intensity of the optical
24 signal received by the lens associated therewith. Amplifier 126 is preferably of the type
25 commercially available from SUNX Sensors USA under the Model Name FX-M1; this amplifier
26 is essentially binary in nature rather than analog, and signals that reflected light is either detected
27 or not detected. The analog output generated by sensor amplifier 128, and the binary output
28 generated by sensor amplifier 126, are coupled to the sensor interface board 124, described in

1 greater detail below in conjunction with Fig. 7. In turn, sensor interface board 124
2 communicates with PLC 120 via the RS232 interface via conductors 121, 123, and 125.

3 Referring now to the circuit schematic of Fig. 7, the light sensor assembly 46 includes
4 level sensor micro-controller 138 located on the sensor interface board 124 (see Fig. 6). Micro-
5 controller 138 is of the type commercially available from Digi-Key Corporation of Thief River
6 Falls, Minnesota under Part No. PIC16F877, manufactured by Microchip Technology
7 Incorporated of Chandler, Arizona. The PIC16F877 is a microcontroller that includes a RISC
8 CPU, 8192 x14 words of FLASH program memory, 256 data memory bytes, and 368 bytes of
9 user RAM. The PIC16F876 also includes a 10-bit Analog-to-Digital converter, includes 33
10 input/output pins, and a universal synchronous asynchronous receiver transmitter (USART) for
11 communications.

12 As indicated in Fig. 7, a 16 MHZ crystal 142 is coupled across oscillator pins 12 and 13
13 of microcontroller 138 to properly clock microcontroller 138. Pull-up resistor blocks 140, 144,
14 146 and 148 are used to "pull-up" the various input and output terminals through a 10K ohm
15 resistor to the positive power supply voltage VDD (approximately 5 volts). Analog input pin 2
16 of microcontroller 138 is coupled by conductor 139 to the output of analog sensor 128 (see Fig.
17 6); analog sensor 128 is the sensor amplifier that is responsive to lens 30 of sensor lens assembly
18 28. Pins 25 and 26 of microcontroller 138 are used as the USART asynchronous transmit signal
19 and asynchronous receive signal, respectively, and are coupled by conductors 143 and 145,
20 respectively, to corresponding terminals of a low power 5 volt RS232 Dual Driver/Receiver chip
21 150 commercially available from Linear Technology Corporation of Milpitas, California under
22 Part No. LT1081. Dual driver/receiver chip 150 interfaces the transmit and receive ports of
23 microcontroller 138 to the RS232 terminals of programmable logic controller PLC 120 within
24 the controller shown in Fig. 6. Also shown in Fig. 7 is a voltage regulator integrated circuit 152,
25 Type 7805 available from National Semiconductor, which receives a + 24 volt power supply at
26 its input terminal, and which provides a well-regulated + 5 volt VDD output power voltage to
27 power the components on the sensor interface board 124.

28 Returning briefly to Fig. 1, it will be recalled that sensor lens assembly 28 includes a

1 second lens 36 and second pair of optical fibers 40 for sensing an "overfill" condition wherein
2 the height of slurry 20 has risen above some maximum safe threshold. Such an overfill condition
3 might result from a failed or misadjusted slurry level sensor. If the overfill sensor has been
4 activated, then the control circuitry within control panel 54 operates a solenoid that permits the
5 full output pressure (70-80 PSI) from the aforementioned main air valve to be applied directly to
6 input port 86 of actuator 84 to immediately shut off the further flow of process fluid through
7 supply tube 22. In this event, the user can regain control over the system by pressing and
8 holding the "clear" button on key pad 58 to clear all alarms, and to de-energize the
9 aforementioned solenoid, in order to once again allow proportional control valve 82 to open and
10 permit slurry to flow therethrough.

11 Overfill sensor lens 36 will indicate an overfill condition when light beam 38 reflects off
12 of a plain metal casting belt or other highly reflective surface, even though there is actually no
13 slurry in slurry reservoir 15. Accordingly, when first starting the system, control valve 82 must
14 be manually opened, as by the user depressing one of the numeric key pad buttons (the "valve
15 open" button) on key pad 58, to allow new slurry to start filling the slurry reservoir 15, and
16 thereby cover the area of the belt within reservoir 15 below sensor lens 36. Once belt 14 is
17 covered with slurry, overfill sensor lens 36 will not indicate an overfill condition again until the
18 height of the slurry 20 in reservoir 15 has become too high. If desired, control panel 54 may
19 include a built-in alarm unit to provides an audible indication of alarm conditions, such as the
20 aforementioned overfill condition. Port 80 on control panel 54 can optionally be used to transmit
21 an alarm signal to remote equipment.

22 The aforementioned direct coupling of the main air valve to actuator 84 during an overfill
23 condition also serves to insure that, in the event of a regulator valve failure, control valve 82 will
24 assume its fully-closed position. For example, if electrical power to control panel 54 should be
25 lost, pressurized air from the main air valve is directly coupled to pressure input port 86 of
26 actuator 84 of control valve 82 to pinch off supply tube 22.

27 To properly set-up control panel 54, one must first determine the slurry level is to be
28 maintained within slurry reservoir 15. The user places a piece of white paper on a precision

1 block that has a thickness equal to the level desired in slurry reservoir 15. This precision block is
2 placed directly beneath sensor lens 30. If sensor lens 30 is too high or too low to detect the
3 presence of the white piece of paper, then the user makes an initial gross adjustment by loosening
4 thumbscrew 48 (see Fig. 3), and manually raising or lowering sensor tube assembly 28 until LCD
5 display 60 shows some amount of slurry reservoir level. At this point, the control panel 54 is
6 turned off, and the precision block and white paper are removed. The level sensor assembly is
7 now ready.

8 Control panel 54 can be operated either in an automatic mode or in a manual mode. The
9 automatic mode of operation will be described first. On power-up, the controller circuitry within
10 control panel 54 automatically starts control at the most recently used Set Point. The Set Point
11 can be changed, if desired, during the automatic mode by depressing the "up" or "down" keys of
12 key pad 58 to increment or decrement the current Set Point level. To save the new Set Point, the
13 user presses the "save" button on key pad 58. The control circuitry within control panel 54 loads
14 all stored values from an EPROM. The aforementioned alarm will sound initially, and the
15 "alarm" button (the numeric "2" button on key pad 58) must be depressed to put the system into
16 "automatic" mode. If a highly reflective surface is directly beneath overfill sensor lens 36, the
17 alarm will not clear. A user presses the "valve-open" button on key pad 58, and holds it until
18 control valve 82 opens to allow slurry to be dispensed into slurry reservoir 15. It will be noted
19 that there is also a "valve-closed" button on key pad 58 which can be used to shut off control
20 valve 82, if desired. In any event, the user continues to depress the "valve-open" button until
21 slurry 20 covers the portion of belt 14 beneath sensor lens assembly 28. Once process fluid is
22 detected below sensor lens 30, a slurry level reading will be displayed by LCD display panel 60.
23 Initially, the displayed slurry level reading will be less than that of the Set Point of the system.

24 As the fluid level increases in slurry reservoir 15 and approaches the Set Point, the
25 control system starts to close control valve 82 to decrease the flow of slurry therethrough. When
26 the sensor detects that the slurry height matches the Set Point level, control valve 82 is fully-
27 closed to pinch-off any further flow of slurry therethrough. In contrast, if the control system
28 senses a drop in the level of the slurry 20 within reservoir 15 below the Set Point level, then

1 control valve 82 begins to open to increase the flow of slurry into reservoir 15. The control
2 system uses a custom PID function to make real-time adjustments to control valve 82 to control
3 the level of slurry within reservoir 15 to within .012 inch of the Set Point level. This automatic
4 mode of operation is the default mode, and controls the slurry level depending upon feedback
5 from the height sensor.

6 In manual mode, the "up" and "down" keys of key pad 58 are used to adjust the flow of
7 control valve 82. Pressing and holding the "up" key increases slurry flow through control valve
8 82, whereas pressing and holding the "down" key decreases slurry flow through control valve 82.
9 The current flow rate is indicated in the upper right hand corner of LCD display 60. When
10 manual mode is selected, the sensor lens assembly 28 has no effect on the position of control
11 valve 82 or the resulting slurry flow rate; if desired, however, sensor lens assembly 28 may still
12 trigger the generation of alarms.

13 The applicant became aware of a phenomena called "backlash," which relates to the
14 inertia of the control valve. It has been noted that, when the direction of valve movement is
15 reversed, the change in air pressure required to cause such reversal is greater than originally
16 anticipated. In effect, flow control valve 82 of Fig. 5 exhibits a form of mechanical hysteresis. If
17 such hysteresis, or backlash, is not compensated, then the relationship between the regulated air
18 pressure and the corresponding slurry flow rate through control valve 82 will not be as linear as
19 desired.

20 The microcode which controls the programmable logic controller (PLC) 120 in controller
21 cabinet 54 is therefore written in a manner to compensate for such backlash. The microcode
22 stores a voltage value that represents a voltage within the 1-5 volt range of the analog output
23 signal driven onto conductor 135 by PLC 120 and input to proportional regulator air valve 136.
24 This value is determined in advance by the process engineer by performing the following
25 operation. The process engineer, would pressurize control valve 82 to a given point, and position
26 a ruler or other distance measuring device adjacent to the valve ram/jaw 102. The engineer
27 would then increase the air pressure applied to port 86 of actuator 84 until ram 102 moved to a
28 new position of smaller separation distance relative to jaw 106. The engineer would then "zero"

1 the measuring device, and begin decreasing the air pressure supplied to port 86 of actuator 84 of
2 control valve 82, while watching both the line input air pressure and the measuring device. At
3 the point where the measuring device shows motion of ram/jaw 102, the engineer takes note of
4 how much the input air pressure was reduced to obtain such movement; in this example, it will
5 be assumed that the input air pressure had to be reduced by 3 psi. The engineer would then enter
6 the Backlash factor as 3 in the microcode for PLC 120. PLC 120 stores a voltage value
7 proportional to the amount of total air pressure that is output by proportional air valve 136 that
8 the backlash factor represents.

9 For example, if proportional air valve 136 puts out a maximum of 70 psi, then 3 psi
10 represents 3/70 of the total analog voltage range, or 3/70 of the 4 volt analog output voltage
11 range (5 volts max minus 1 volt min), or .1714 volts. This value remains a constant as long as
12 the factor remains set at 3 psi. During start-up of the level control system, PLC 120 initially
13 causes the analog output voltage conducted by conductor 135 to its maximum voltage of 5 volts
14 for directing proportional air valve 136 to apply maximum pressure (70 PSI) to actuator 84 of
15 control valve 82. Thus, any subsequent movement of such analog output voltage must be in the
16 negative direction (i.e., less than +5 volts). PLC 120 keeps track of the past two values of such
17 analog voltage; hence, PLC 120 can compare such values and recognize when the direction of
18 valve movement has changed. For example, if PLC 120 originally produced an analog voltage of
19 4.5 volts, then 4.3 volts, followed by 4.4 volts, then PLC 120 would know that the direction of
20 valve movement has changed; PLC 120 would then add or subtract (depending on the direction
21 of the change) the backlash factor voltage to the new targeted output voltage in order to
22 overcome the backlash of the valve. In this example, the new analog output voltage driven by
23 PLC 120 onto conductor 135 would be 4.4 volts plus the backlash factor of .1714 volts, or
24 4.5714 volts.

25 Those skilled in the art will now appreciate that an improved level control system,
26 suitable for use in, among other things, tape casting processes, has been described which more
27 accurately controls the thickness of the cast tape produced. It will be appreciated that the
28 disclosed apparatus is relatively inexpensive and simple to construct, and that it reduces the risk

1 of explosion by isolating electrical spark-generating components from the volatile atmosphere of
2 the process fluid. The disclosed level control system allows the slurry fluid level to be monitored
3 in real time, and rapidly adjusts supply flow rates to maintain a desired level. While the present
4 invention has been described with respect to a preferred embodiment thereof, such description is
5 for illustrative purposes only, and is not to be construed as limiting the scope of the invention.
6 Various modifications and changes may be made to the described embodiments by those skilled
7 in the art without departing from the true spirit and scope of the invention as defined by the
8 appended claims.

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